

Engine Efficiencies in Irrigation Pumping from Wells

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ABSTRACT

TWO hundred forty natural gas-powered engines and 26 diesel engines were efficiency tested on irrigation pumping plants in the Texas High Plains. Average thermal efficiencies for the natural gas-powered and diesel engines were 20.5 and 31.2%, respectively. Individual natural gas-powered engines ranged from 7.8 to 28.9% efficiency with industrial type engines designed for gaseous fuel being the most efficient. The range of diesel engine efficiency was much narrower, 26.0 to 34.8%, and for all diesel models tested, one or more engines exceeded 30% efficiency. Engines that tested more efficiently in the laboratory according to manufacturers literature consistently tested more efficiently in the field.

INTRODUCTION

Because of escalating petroleum prices during the past decade, the efficiency of internal combustion engines used for pumping from wells has become critical for profitable irrigation. Most natural gas-powered engines used for irrigation pumping are located in the Great Plains while diesel engines are used throughout the United States to power irrigation pumping plants (Gilley, 1980). Measuring the in-place efficiency of the engines is seldom done commercially because torque measuring equipment and driveline adapters are needed. Up-to-date efficiencies of irrigation pumping engines would show equipment needs and the economic feasibility of engine efficiency testing.

Although a number of irrigation pumping plant efficiency tests have been reported during the past 30 years, studies reporting field measurements of engine efficiency are limited. In a study on the Southern Plains, the thermal efficiency of 46 natural gas-powered engines averaged 19.8% and ranged from 3.7 to 30.8% (Texas Tech College, 1968). In a similar study in New Mexico, Abernathy et al. (1978) reported average efficiencies of 21.4% for 285 natural gas-powered engines and 28.9% for nine diesel engines. In a more recent study in one water district in the Texas High Plains, the efficiency of 91 natural gas-powered engines averaged 20.6% (The Cross Section, 1980). These studies showed somewhat

low efficiencies for engines powered by natural gas with no temporal efficiency trends. The number of diesel engines tested in previous studies has been insufficient to make any conclusions about field efficiencies.

The performance criteria developed by Schleusener and Sulek (1959) for appraising the operating efficiency of irrigation pumping plants have become widely used. The criteria stated in horsepower-hours and water horsepower-hours per unit of fuel were derived from manufacturer's engine and pump data and the Nebraska tractor tests. For natural gas-powered and diesel engines, the performance criteria are 2.34 kWh/m³ (88.9 hp-h/1000 ft³) and 2.87 kWh/L (14.58 hp-h/gal), respectively. Recently, the University of Nebraska (1982) increased the performance criteria for diesel engines to 3.28 kWh/L (16.66 hp-h/gal). Since the criteria are based on a 75% pump efficiency and a 95% right angle gear drive efficiency, engine efficiency can be calculated for fuel with a known heating value.

The objective of the study reported here was to test a sufficient number of natural gas-powered engines and diesel engines to establish bench-mark engine efficiencies for irrigation pumping across the entire Texas High Plains. We did not develop engine tuning techniques in the field or retest engines after the owners had them retuned.

PROCEDURES

All engines were tested in place under normal operating conditions for the irrigation pumping plant. To do this, the power transmitted from the engine to the right angle gear drive and the rate of fuel consumption were measured. Engine torque and speed were included in this measurement. The heating value of the fuel was also measured or data from measurements by others were collected. Sufficient information was recorded to classify each engine using common terminology. The pumping rate, pumping lift, pump discharge pressure, and pump speed were also measured. Data for the pumps and pumping plants will be published in other reports.

Engine output was measured by removing the U-joint driveline and installing a temporary driveline with a torque meter and shaft speed indicator. The researchers at Texas Tech College (1968) developed this procedure for on-farm irrigation engine testing. The strain gage torque meter was a rigid extension of the horizontal shaft of the right angle gear drive, and a shorter U-joint driveline connected the engine to the torque meter. The shaft speed indicator was an integral part of the torque meter. A micro-processor converted torque and shaft speed values to power values, and a digital readout sequentially displayed the torque, shaft speed, and power.

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Natural gas measurements were made with a commercially available diaphragm meter. The flow volume was timed with a stopwatch, the gas flow rate was calculated, and the measurement was repeated three or more times. Gas pressure on the discharge side of the meter was measured, and gas volumes were corrected to standard atmospheric pressure.

Diesel fuel was measured volumetrically with a calibrated cylinder made of plexiglas. During the test, the calibrated cylinder replaced the permanent fuel tank. The diesel fuel temperature was also measured, and the volume was corrected to the volume of calorimeter tests.

Although specific fuel consumption is usually preferred by automotive engineers as an indicator of engine efficiency (Obert, 1968), specific fuel consumption was converted to thermal efficiency for easier data interpretation. With thermal efficiencies, comparison of engines powered by natural gas and diesel is more meaningful. With the heating value of the fuels, the thermal efficiencies can be converted to any desired specific fuel consumption. The results can also be directly compared with the earlier studies of engine efficiency in irrigation pumping.

To obtain the heating values, the heating value of diesel fuel was measured and natural gas heating values were obtained from the power companies. Long-term measurements of natural gas in the Texas High Plains have shown a consistent heating value of 37.3 MJ/m³ (1000 BTU/scf) for processed gas and 44.7 MJ/m³ (1200 BTU/scf) for unprocessed wellhead gas. With standard calorimeter tests, a heating value of 37.6 MJ/L (135,000 BTU/gal) was measured for the diesel fuel used in the study.

The displacement, model, and manufacturer were the three main identifiers for the engines. Automobile or truck engines modified for stationary use with natural gas were identified as automotive engines and engines designed for stationary use with natural gas were identified as industrial engines. The major modifications for the automotive engines were removal of the radiator and fan and substitution of a gaseous fuel carburetor. Engines were also identified as turbo-charged or naturally aspirated. The engine data plate was often the only source of information, so the design compression ratio, type of carburetor, and age of the engine usually could not be determined.

RESULTS

Efficiencies for the natural gas-powered engines and the diesel engines are listed in Tables 1 and 2, respectively. For each engine model, the number of engines tested, the engine type, and the low, high and average efficiencies are listed. The thermal efficiency of 240 natural gas-powered engines averaged 20.5% and ranged from 7.8 to 28.9%. For the 26 diesel engines, the thermal efficiency averaged 31.2% and ranged from 26.0 to 34.8%.

Efficiency distributions for a popular automotive engine and a popular industrial engine are illustrated in Figs. 1 and 2, respectively. In Fig. 1, the efficiency for 19 similar automotive engines is only 19.8% and no efficiencies exceeded 24%. For the industrial engine illustrated in Fig. 2, the average efficiency of 61 engines is 22.3% and the efficiency of 13 engines exceeded 24%. Displacements of the automotive and industrial engines

TABLE 1. THERMAL EFFICIENCY OF NATURAL GAS POWERED ENGINES AVERAGED FOR EACH ENGINE MODEL TESTED

Engine	Engine type*	No. tested	Low, %	High, %	Avg., %
1	I	1			16.1
2	I	1			28.0
3	I	2	26.3	26.3	26.3
4	A	28	12.4	23.2	18.8
5	A	2	17.3	23.2	20.3
6	A	3	17.8	17.9	17.9
7	A	4	17.7	19.4	18.4
8	A	19	13.8	24.7	19.8
9	A	6	17.0	23.2	19.9
10	I	1			21.6
11	A	4	20.7	21.4	20.9
12	A	11	18.1	23.2	21.0
13	A	5	18.1	22.7	19.6
14	A	14	16.9	22.0	19.3
15	A	2	18.3	21.0	19.7
16	A	5	19.0	23.8	21.5
17	A	2	19.9	20.1	20.0
18	I	5	18.2	23.8	20.5
19	I	2	21.6	22.7	22.2
20	I	3	14.1	16.9	15.6
21	I	16	16.5	23.8	20.2
22	I	61	14.1	28.9	22.3
23	I	10	21.2	26.5	24.3
24	A	1			21.8
25	I	4	21.2	22.1	21.7
26	I	8	15.5	19.2	17.6
27	I	1			19.4
28	Unknown	3	7.8	17.0	13.4
29†	A	16	15.3	24.7	19.1
All engines		240	7.8	28.9	20.5

*A - Automotive, I - Industrial

†Tandem automotive engines

are 6.77 L (413 in³) and 13.1 L (800 in³), respectively. We did not test a sufficient number of any model of diesel engine to develop efficiency distribution graphs.

Fig.3 illustrates the relationship between the manufacturers laboratory efficiency and the average field efficiency for seven engine models. For each of the models, eight or more engines were tested, and manufacturers efficiency data were available. With each

TABLE 2. DIESEL ENGINE THERMAL EFFICIENCY AVERAGED FOR EACH ENGINE MODEL TESTED

Engine	No. tested	Low, %	High, %	Avg., %
1	1			34.3
2	1			31.5
3	1			32.0
4	4	32.0	34.3	32.8
5	1			31.5
6	1			30.4
7	1			30.9
8	2	32.5	33.1	32.8
9	5	26.0	34.8	29.9
10	1			32.0
11	3	27.0	32.0	29.7
12	5	28.6	31.5	30.2
All engines	26	26.0	34.8	31.2

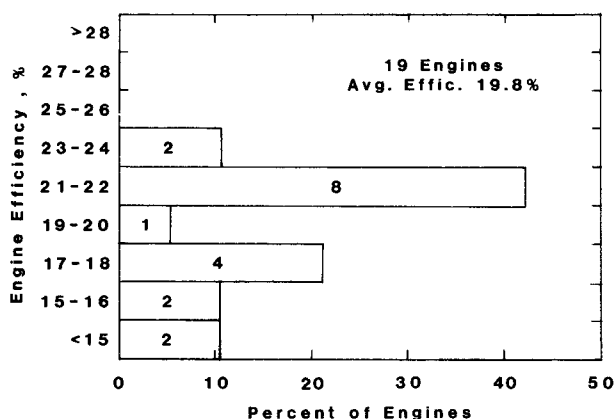


Fig. 1—Thermal efficiency distribution for an automotive engine.

1% increase in laboratory efficiency between 23 and 32%, the average field efficiency increased 0.58%.

In Fig. 4, engine efficiency as a function of engine power is illustrated for a small automotive engine and an industrial engine. For each of the engines, efficiency varies linearly with power output. For each kilowatt increase in engine power output, the efficiencies of the automotive and industrial engines increased 0.20 and 0.068%, respectively. The coefficients of determination (r^2 values) show that 42% and 66%, respectively, of the variability in engine efficiencies were associated with engine power output.

DISCUSSION

Most of the natural gas-powered engines tested during the study did not operate at a high efficiency. If the Nebraska performance criteria (Schleusener and Sulek, 1959) for irrigation pumping plants powered by natural gas is divided into component efficiencies, the engine efficiency with 37.3 MJ/m³ (1,000 BTU/scf) natural gas is approximately 24%. Two-thirds of the engine models reported here did not have any engines testing 24% or higher. Only 16% of the 240 engines tested equaled or exceeded the performance criteria. Thus, the Nebraska performance criteria is difficult to attain with most natural gas-powered engines now operating in the Texas High Plains.

Most diesel engines tested during the study were operating at relatively high efficiencies. If the revised Nebraska performance criteria (University of Nebraska,

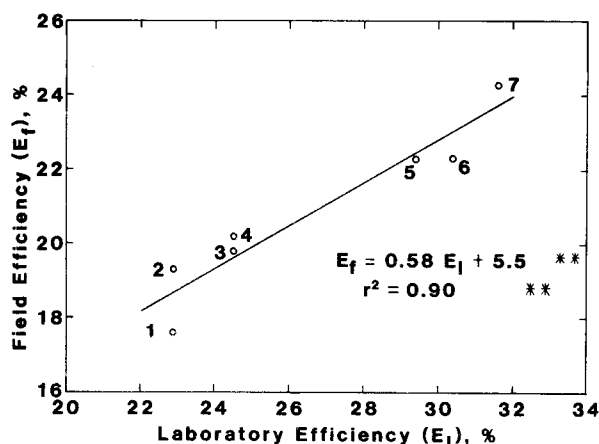


Fig. 3—The effect of laboratory efficiency on the average field efficiency for seven engine models. Data for the laboratory tested engines are listed in Table 3. **Statistically significant ($P=0.01$).

TABLE 3. ENGINE TYPE, COMPRESSION RATIO, DISPLACEMENT, AND RPM FOR THE ENGINES ILLUSTRATED IN FIG. 3

Engine no.	Engine type	Compression ratio	Displacement, L	RPM
1	I	7.2:1	13.4	1200
2	A	7.3:1	8.7	2350
3	A	7.5:1	6.8	2100
4	I	7.1:1	9.9	1150
5	A	*	9.9	2200
6	I	8.0:1	13.1	1400
7	I	*	13.1	1400

*Unknown.

†Turbocharged.

1982) for irrigation pumping plants powered by diesel engines is divided into component efficiencies, the engine efficiency with 37.6 MJ/L (135,000 BTU/gal) fuel is approximately 33%. Six of the 26 engines equaled or exceeded the standard, and for all models tested, one or more engines exceeded 30 percent efficiency.

The higher inherent efficiency of diesel engines due to higher compression ratio and a more efficient thermodynamic cycle was illustrated by the field data.

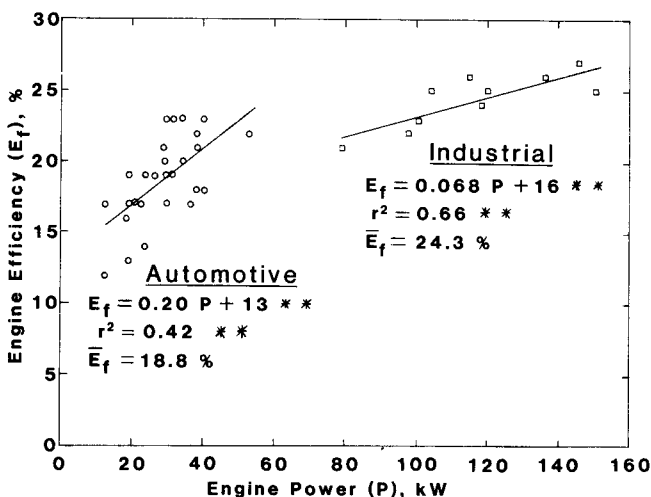


Fig. 4—Engine efficiency as a function of engine power for a 4.79 L (292 in³) automotive engine and a 13.1 L (800 in³) industrial engine. The automotive engine was rated at 48 kW (64 hp) at 2,200 rpm and the industrial engine was rated at 133 kW (178 hp) at 1,400 rpm. **Statistically significant ($P=0.01$).

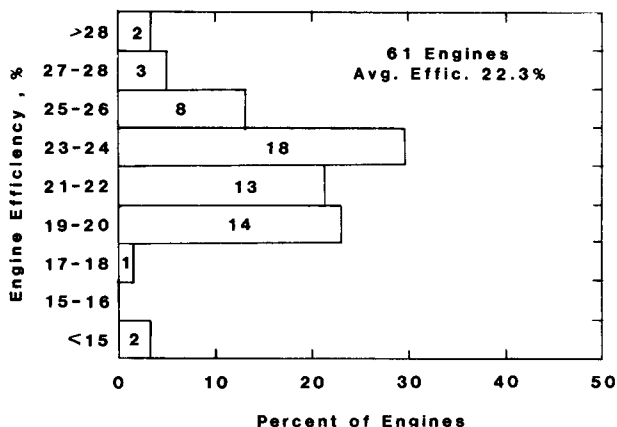


Fig. 2—Thermal efficiency distribution for an industrial engine.

Average thermal efficiency of the diesel engines was 1 1/2 times as high as the average for the natural gas-powered engines. This difference in efficiencies is large enough that it must be considered when comparing fuel costs on an energy unit basis. Diesel engine efficiencies ranged from 26.0 to 34.8% while the efficiency of natural gas-powered engines ranged from 7.8 to 28.9%. the narrower efficiency range was caused by the absence of low efficiency diesel engines.

The efficiencies of the natural gas-powered engines were not statistically different ($P=0.05$) from those reported by earlier investigators. The average efficiencies reported by Texas Tech College (1968), Abernathy, Cook, and Dean (1978), and The Cross Section (1980) were 19.8, 21.4, and 20.6 percent, respectively. Thus, the 20.5% average efficiency for the 240 engines reported here does not indicate a temporal or geographic trend. Instead, it suggests that engine selection and maintenance are similar throughout the irrigated region where natural gas is used to pump irrigation water. The thermal efficiency of the 26 diesel engines averaged 2.3% higher than the 28.9% average reported by Abernathy et al. (1978).

Comparison of automotive and industrial natural gas-powered engines showed higher potential efficiencies for the industrial engines. An absence of automotive engine efficiencies above the Nebraska performance criteria was notable. The efficiency distribution graph for the automotive engine (Fig. 1) is typical of all automotive engines tested. Even if the engines were well-maintained and properly sized for the pumping load, the efficiency did not exceed 24%. For several of the industrial engine models, however, individual engines tested above the Nebraska performance criteria. The industrial engine efficiency graph (Fig. 2) illustrates the higher potential of some industrial engines. Although efficiencies could be quite low, well-maintained and properly sized engines often exceeded 24% efficiency.

The design efficiency of natural gas-powered engines is an important consideration in obtaining high engine efficiency under field conditions. For the engines illustrated in Fig. 3, the laboratory efficiency obtained from manufacturers specific fuel consumption data ranged from 23 to 32%. This large variation in laboratory efficiency consistently carried over into the field. For each 1% increase in laboratory efficiency, the average field efficiency for the engines increased 0.58%. Thus, reliable engine efficiency data is a starting point in selecting efficient natural gas-powered engines. the higher efficiencies can be evaluated along with the higher initial cost to select an engine with the lowest total cost.

Generally, engine efficiency was directly related to the power output of the engines. For engine models for which we tested ten or more engines, we fitted linear regression curves to the engine efficiency and engine power data, Fig. 4. Regression coefficients were all positive, and most were statistically different from zero ($P=0.05$). In Fig. 4, the 0.42 and 0.66 coefficients of determination show that a significant part of the variation in engine efficiency was due to the level of

power output. All of the coefficients exceeded 0.30, so the data of Fig. 4 are representative of the engine models analyzed statistically. There was no indication that engine efficiency was decreased by loading to maximum power output. The number of diesel engines tested was insufficient to correlate engine efficiency and engine power output.

A mismatch in the power characteristics of pumps and engines is common in the Southern High Plains, where a declining water table is decreasing the saturated thickness of the Ogallala Aquifer. With the declining water table, pumping rates decrease faster than pumping lifts increase, and engines are seldom loaded to maximum power. For most natural gas-powered engine models, the minimum power output was about 30% of the maximum power output. The remaining power outputs were somewhat uniformly distributed between the minimum and maximum values.

Careful engine selection can improve engine efficiency without appreciably increasing the engine cost. For example, the engines with the highest and lowest efficiencies illustrated in Fig.3 were both heavy duty industrial engines of similar cost. Yet the lowest efficiency engine was using 39 percent more fuel per unit of energy output than the highest efficiency engine. If an engine is selected for the maximum recommended continuous power output, the efficiency will probably be higher than for lesser power output and the cost will likely be less than for a larger engine of similar quality.

CONCLUSIONS

1. The 20.5% average thermal efficiency of 240 natural gas-powered engines was not statistically different from the average efficiencies reported in earlier studies.
2. The average thermal efficiency of diesel engines was 1 1/2 times as high as the average efficiency of natural gas-powered engines.
3. High field efficiency of natural gas-powered engines was correlated with high manufacturer's laboratory efficiency.

References

1. Abernathy, G. M., M. D. Cook, Jr. and J. W. Dean. 1978. Improving the efficiency of natural gas irrigation pumping plants. Technical Report NMEI 12. New Mexico Energy Institute, New Mexico State University. 18 pp.
2. Gilley, J. R. 1981. On-Farm U.S. Irrigation Pumping Plants. Report No. DOE/SEA-7315-20741/81/1. 43 pp.
3. Obert, E. F. 1968. Internal combustion engines., 3rd ed. International Textbook Co., Scranton, PA. 736 pp.
4. Schleusener, P. E. and J. J. Sulek. 1959. Criteria for appraising the performance of irrigation pumping plants. *Agricultural Engineering* 40(9):550-551.
5. Texas Tech College. 1968. Power requirements and efficiency studies of irrigation pumps and power units. Special Report No. 19. International Center for Arid and Semi-Arid Land Studies, Texas Tech University, Lubbock. 79 pp.
6. The Cross Section. 1980. Tests show 60% efficiency attainable. *The Cross Section* 26(11): 1-2.
7. University of Nebraska. 1982. Irrigation pumping plant and well efficiency handbook. Cooperative Extension Service, Institute of Agriculture and Natural Resources, University of Nebraska, Lincoln, Fourth Edition, 284 pp.